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ABSTRACT

This paper surveys the types of computer usage, both current and planned, in science education. The authors state that they are concerned not with the scientist with computer experience, but rather with telling those without computer teaching experience about the possibilities and prospects. In their discussion, the authors distinguish at least five modes of usage, each embracing several types of output: alphameric or graphic, paper or film, and temporary or permanent. the five modes are: (1) producer of materials, (2) administrator, (3) tutor, (4) simulator, and (5) calculator. It is as a calculator that the authors feel the computer demands the most understanding and participation of the student, and the computer should have its greatest impact in science teaching. Various facilities utilized are summarized under these headings: interactive, semi-interactive, and non-interactive. Several graphic display systems are described as interactive systems. The conclusion discusses the authors' concepts of how computer usage might alter the style and content of science education. (TS)

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Computers in the Science Curriculum

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Introduction

The scientist has, during the past few years, seen the computer loom larger and larger in his research activities. However, except in a few locations, the teaching of science has ignored the existence of the computer. The small group of scientists who have used the computer as a teaching device, while often acutely conscious of the current limitations of the digital computer in the classroom[1], have been very enthusiastic about what is possible.

This paper surveys the types of computer usage in science education, both current and planned. We are concerned not with the scientist with such experience, but rather with telling those without computer teaching experience about the possibilities and prospects. As the type of use may depend on the facilities available, we will start with computer equipment used in teaching.

Facilities

The use we make of computers will depend in part upon the available facilities, which, from the pedagogical point of view, may be generally classified as interactive, semi-interactive or non-interactive. This classification is certainly not rigorous. The most significant criteria suggesting this classification are (1) "turn-around time," the time between the submission of a request and the receipt of results; and (2) the "debugging" or error-correcting capabilities.

Debugging may be "on-line" or "off-line;" on-line means that a process is performed while one's program is currently active in the computer, perhaps in the central processing unit (CPU), the part of the computer which does arithmetical and logical operations. Conversely, "off-line" means that a process is carried out without connection with the CPU. Table 1 illustrates the rough classification by means of these criteria, based on the most common practices.

Often large computers which process groups of programs one after another from card or tape input are <u>non-interactive</u> in that the turn-around time may be of the order of hours or days. Such processing is known as "batch-processing." Errors in programming cause the termination of the program, so that several attempts are usually necessary to achieve a first successful run, often resulting in a delay of days. An enormous variety of powerful computer languages is available for "batch" use which, for many calculations, is the cheapest way to do the job. Currently, most medium- and large-scale computers are operated in a non-interactive mode.

A diverse collection of computer systems fits into the gap between truly interactive systems and non-interactive batch systems. We have chosen to refer to these as <u>semi-interactive</u> computers. Here we are not talking about a single type of computer or programming system, but rather an entire spectrum of facilities. As semi-interactive, we may designate those installations where turn-around times of the order of minutes enable the student to quickly debug and resubmit his programs with only a relatively short time elapsed before results are obtained.

Table 1. Facilities.

Facility	Turn-around	Debugging
Interactive	Seconds	On-line
Semi-interactive	Minutes	Off-line
Non-interactive	Hours	Off-line

One kind of semi-interactive system might be described as a fast batch system. These systems are batch in the sense discussed above, but the programming system is structured such that a small job has a high priority, and so goes quickly through to completion. Such computers may use remote job-entry facilities, with input and output terminals at some distance from the CPU. The price scale may reflect the priorities requested; low priority jobs can be run at times when there is little system demand and are charged less accordingly. This type of facility is generally combined with multiprogramming where several programs are currently active at the same time in the CPU, or in several CPU's working together; large batch computers are also making increasing use of multiprogramming.

In a fast batch remote job system the remote terminal can be complex, having a card reader, a line printer, and other facilities far exceeding in speed those available at the usual typewriter console of the interactive systems to be described. A small computer may also serve as such a terminal.[2] Recently, the United States Office of Education has been discussing a large fast batch remote entry system for use in educational environments in American high schools, a system capable of serving one or two hundred thousand students, with limited access to an algebraic programming language.[3]

Another type of semi-interactive system is based on the small stand-alone computer, used in an "open shop" fashion. Here the students use the computer directly, not working through the programming and operational staff of the computer facility. Programs are executed as soon as prepared by the student; the student operates the computer.

He or she can also immediately re-enter programs with corrections to take care of errors which occurred during the initial run. As many as ten or so students can effectively use the computer simultaneously, provided it is in a room with a number of keypunches or paper tape punches for separately preparing the program input without using up machine time. Learning to operate such a computer is usually a simple process.

Almost any small machine can be used semi-interactively in this manner, although those with disc monitor systems, such as the IBM 1130, are the most convenient from the users point of view. In many situations this type of semi-interactive facility is very competitive economically. In the long run, such machines are currently cheaper than time-sharing consoles, to be discussed below, and provide more computing time; however, the available languages are sometimes harder to learn. Especially in high schools and small colleges, the small stand-alone computer can be used in many educational applications with great convenience. However, not all types of teaching usage we will discuss here can be run on such a system. In particular, the programmed instructional uses, to be referred to later, would be difficult with a single small machine.

An <u>interactive</u> computer facility is one that provides almost instantaneous response for the student. The commonest and cheapest interactive computer system is based on the time-shared typewriter-like console, which can be installed wherever there is an electrical outlet and a telephone. These devices can also be hard-wired directly to the computer. The console may have a paper tape reader, also

so that programs can be prepared off-line and then quickly fed into the console when it is connected (on-line) to the computer. A console typically rents for about $1000 per year. Many such devices simultaneously use one machine; the number can run into hundreds, and systems with thousands of consoles are being discussed.

The student types his program, either directly to the computer or onto the paper tape which is then fed into the teletype. If a telephone connection is used, the information is converted by a "dataset" into signals which go out over telephone lines to any computation center whose telephone you can dial. By reversing this procedure, the computer can cause its responses to be typed on your console. Answers to short programs are almost immediate, and one rarely waits long except during extensive calculations. Quoting from Kemeny and Kurtz of Dartmouth, "We have found that any response time which averages more than ten seconds destroy the illusion of having one's own computer. Such times are rare at Dartmouth."

Typewriter consoles provide easy computation for simple problems; the languages are generally easy to learn; access to the computer and debugging are easy as compared with non-interactive computer systems. Commerical time-sharing facilities often provide a library of programs convenient for some uses, but not for educational uses. Time-sharing is generally not effective for programs which are large or complex, and storage of programs on disks at the central time-sharing computer, although very convenient, is generally a major item of expense.

Time-sharing service is supplied by many commercial firms, but university and research laboratory installations increasingly have their own time-sharing system. The cost of student usage on a commercial system may average $16-$20 per hour, with charges distributed in various ways between on-line "connect-time" and actual CPU time. Thus, as a rule of thumb, if more than 100 hours/month of teletype usage is expected, it might be advisable to invest in a small semi-interactive facility, unless the interactive nature of time-sharing is particularly relevant.

For many student problems in science, programs are short and the actual computation time almost negligible -- more money may be spent on terminal time (just sitting and thinking in front of the console while connected to the computer) rather than on actual computing.

Kemeny and Kurtz, describing the pioneering time-sharing venture at Dartmouth College,[4] where they have sixty time-shared teletypes using the BASIC language, noted that eighty percent of all Dartmount students and a "significant" part of the faculty learned to program for time-sharing, and that "two one-hour lectures are entirely adequate to introduce the novice to BASIC". In the computer training session, given as part of freshman mathematics, they found that: "The typical training session results in about ninety-five percent completion of all assigned problems, a figure so high that it testifies to the universal enthusiasm of the students..."

An alternate approach to learning to use an interactive system has been tried at the University of California, Irvine. The method is analogous to learning about a strange animal by observing its behavior under selected stimuli. The student is asked to type things at the console; he watches the response of the system and answers questions based on this response. Again about two hours are all that is needed to have a student ready to write his own programs. This procedure has been successful with several different time-sharing languages.

One type of interactive system just coming into use is a time-sharing system on a small computer. Until recently any truly interactive system, offering rapid response to the user, almost inevitably used a medium-or large-scale computer. Thus, the system being used in time-sharing were typically in the half-million dollar range and upwards. Recently, however, several small time-sharing systems based on small computers such as the PDP-8, the Hewlett-Packard 2001 or the IBM 1130 have been developed. Small systems do not provide as wide a range of languages as the larger systems, and they do not allow as many terminals. Nevertheless, in many situations they may represent a viable alternative to a large interactive time-sharing system.

Graphic Terminals

Another type of terminal often used interactively is the cathode ray tube (CRT) display, in essence a precisely-controlled oscilloscope. The most advanced CRT's use 2^{20} to 2^{27} addressable points on a cathode

ray tube face; the computer can be programmed to display a point or a character, or to draw a line between two points. The programmer can interact with the computer through the CRT console in at least three ways: (1) a typewriter keyboard allows alphameric (alphabetic/numerical) input; (2) programmed function keys can initiate various pre-defined operations on the display, which are created by the programmer; (3) electronic analog devices such as the lightpen, electronic tablet, "mouse", and "joystick" may be activated to supply graphic information directly to the computer without the need of prior processing by the operator's program or graphics system software.

The lightpen contains a photocell which detects the passage of the electron beam across the CRT screen and so returns information about the time (and therefore location) of the beam detection. The electronic tablet continually supplies the computer with the position of a stylus on a notebook-sized surface. Mouses (not mice) are devices which roll on wheels around on a table and place a cursor symbol on the screen depending on how they are rolled. Joysticks are devices which resemble airplane control sticks in appearance; they are two-dimensional potentiometers which deliver voltages that result in immediate changes in the image on the screen. They can, for example, be used to simulate navigation of a vehicle in space in a very realistic way. The information returned by such devices can also be used as inputs to various pre-defined branches of the program by pushing the appropriate function keys.

The most expensive and sophisticated CRT's contain all three modes of interaction. The displays are continuously regenerated (refreshed) from information stored in buffers which can be filled and altered from the computer. A second, less expensive, type of CRT is restricted primarily to alphameric display; only limited graphic work is possible. The 1510 model in the IBM 1500 system, developed for computer-assisted instruction (which we will discuss later), is of this type. Such a display can be used to present instructions or tests to students and accept responses. It is interactive to the extent that students may type in their answers to questions or indicate multiple-choice responses with a lightpen, but it has no programmable function keys.

Also in existence are time-sharing facilities employing TV sets which accept the same signals as teletypes or typewriters and produce the same characters, so that the TV itself, with its own keyboard, is functionally equivalent, except for speed, to the typewriter in producing the receiving signals. A few experimental TV systems with extensive graphic capabilities have been constructed, and such systems may soon be more commonly available. They can use inexpensive, mass-produced TV sets to reduce costs, and computer-generated output can be easily combined with video-taped material.

Another type of visual interactive system is based on a "storage" CRT as the output device; the internal mechanism of the oscilloscope continuously maintains the image so the picture, once drawn on the tube, remains until the "erase" button is pushed, either by the computer or by the viewer. Thus, the problems of "refreshing" the screen are not

present. Furthermore, the amount of information that one needs to transfer to the screen is also very much reduced, so that time-sharing of such terminals is more practical. Although storage terminals cannot do everything that the most expensive cathode ray tubes can do, they can accomplish a good measure of both the graphic and alphanumeric capabilities of the larger system at a considerably lower cost in terms of the graphic device, line costs and demands on CPU time.

At least two such storage-type graphic display systems have been used in educational contexts. The original one was developed by Glenn Culler and Burton Fried, and has been in use for several years at the University of California, Santa Barbara. The second system was developed by Anthony G. Oettinger, at Harvard University. Both of these systems are based on a double keyboard, a typewriter keyboard combined with a larger functional keyboard, a keyboard whose keys indicate mathematical and graphic operations which the system can perform.

Both systems take the viewpoint that the user is working with functions. These are actually arays of real or complex numbers within the system, but the beginning user can work as if he were manipulating and displaying functions. Thus, with a few key-pushes, the student can exhibit a function and display its derivative, add it to another function, etc. Or he can do mapping in the complex plane, putting a circle or grid in the plane and then watching how it behaves under conformal transformation. Such systems are primarily software developments; large amounts of programming backup are required in addition to the terminal.

Cathode ray tube terminals may also be used as non-interactive "microfilm recorders" with a camera attachment controlled by the computer and used to photograph each display as the computer constructs it. By varying parameters from picture to picture one builds a sequence of related pictures and thus a computer-animated film.[5]

The lack of convenient permanent copy ("hardcopy"), which is a drawback to the educational use of interactive CRT's, may be overcome by having a group of CRT's served by a single graphic output device, such as an XY-plotter or microfilm recorder (or even a line printer). At the push of a button on a given interactive console, the output device will read the graphic data from the appropriate memory cells assigned to that console, and create a permanent record of the image displayed. Hard copy of alphanumerical data can also be obtained.

For the most part, such graphic facilities as we have mentioned above are not economically feasible at present for use with large numbers of students; however, their educational potentialities are great. Bitzer[6] claims that with the use of gas discharge displays and a large network devoted to time-shared consoles, costs can be much reduced.

Usage

We will not attempt a complete survey of what is being done in computer usage in education; but will instead examine the different categories of usage and give some examples. In discussing the use of the computer, we can distinguish at least five modes of usage, each embracing several types of output: alphameric or graphic, paper or

film, temporary or permanent. The five modes are (1) Producer, (2) Administrator, (3) Tutor, (4) Simulator and (5) Calculator, listed roughly in order of increasing demands on the students' understanding and participation. Although these distinctions are not mutually exclusive, they are useful.

The computer as a producer of materials for use with students is still little known by most teachers. Perhaps the area in which most educational production has taken place is in the making of films. The same computer program which describes the appearance of each frame of the film may also make extensive calculations as the basis for "drawing" the frames. Such films can often give the student a view of the behavior of a mathematical entity, such as a differential equation, that is difficult to obtain in any other way, one that might complement a later analytical view. The films of this type already available, particularly in physics and mathematics, are exciting, but only a beginning.[5] Similar techniques can also be used to produce slides and illustrations. Particularly when much calculation is required, this method is often economical as well as accurate, and sometimes it is the only method feasible.

Another area where computers may soon assist the teacher in developing educational materials is in textbook writing and production. Typewriter terminals, on-line to computers, can be used with powerful editing languages in the preparation of text material; this material can be continually modified by the instructor, with no necessity to have the bulk of the material retyped.

Administrator

The computer can be used as a manager to administer exams, grade them, recommend individually-tailored reading assignments to students based on their grades, given students information about their performance in the course, and carry out other onerous clerical chores connected with teaching.[7] This aspect of teaching is particularly critical with large classes, because the teacher with many students cannot spend large amounts of time with all of them. Many student questions could be efficiently handled by a responsive computer network, using large data bases of student information. Thus the perennial student concern with how he is progressing (what problems is he missing, how did his score on the last exam compare with that of others in the class) could be taken care of with an efficient information retrieval system.

A computer-managed instruction (CMI) system can assist the instructor by providing him with diagnostic information for making decisions concerning course content, structure, lesson schedules, supplementary materials, grouping of students on various "tracks" and prescriptions for individual assistance. Since CMI does not necessarily require that students be on-line to a computer (exams could be administered as multiple-choice in the conventional way), it is less expensive than some of the systems we will discuss below, and does not have to directly intrude into the classroom. We may expect its widespread use to be feasible in the immediate future.

During the 1967-68 academic year Florida State University gave a completely computer-administered physics course for non-scientists to forty students chosen at random from a class of 750.[8] The interactive terminal was the CRT of the IMB 1500 system; input and output was all alphameric; there were no lectures and no live demonstrations. Students were instructed by the computer to listen to tapes and to watch film loops. They proceeded at their own pace, took the same tests as the main body of students, and, as a group, received higher grades. The usage of this system was primarily tutorial, and the results, which may or may not prove to be significant, were suggestive.

Tutorial

In the tutorial mode, the computer is programmed to converse with the student. It can give information to the student, ask him questions, and react to his responses through a typewriter, CRT or an ordinary time-sharing teletype console. Or it can respond to student questions. Many different strategies are possible.

Tutorial logic may be classified as linear, intrinsic, adaptive, or Socratic, according to the degree of complexity of the feedback and branching which the program undertakes as the result of a student's responses.[9] Thus, the linear program is a very straightforward question and answer, the only individual distinctions being the time it takes a student to finish, since every student sees and answers the same questions. The similarity to programmed instruction is obvious. In the case of the intrinsic program the questions asked of

the student will to some extent be influenced by his responses to the preceding question. Thus some limited branching is possible; if the student makes a "wrong" answer, he might be shunted into a "help" sequence, and receive information and questions not seen by other students. The use of a computer as a drill-master, as with practice in elementary reading and arithmetic, might also be grouped here.[10]

In the adaptive mode the questions presented may be dependent on previous answers and on other information about the student stored in the computer. Such a program, in principle, could be very responsive to individual needs.

In the Socratic mode we have a dialogue in which the student, in addition to responding to questions, can also query the machine, ask for hints, require information and so forth. This is the most complicated tutorial mode of all. Student queries would have to be structured to correspond to the recognition capabilities of the language used.

One common approach to tutorial computer assisted learning is through the development of author languages whereby the teacher readily constructs teaching programs. Such a language must allow one to enter text and questions without worrying about formatting, specify both right and wrong answers and the prescribed responses given to each, and what to do in the case of unanticipated wrong responses. It should have the ability to count errors, to store

responses, to grade, and to provide instructors with a permanent record of performance. Also desirable is the provision of computational facilities through the interactive terminal, so the student can, if desired, actually solve problems by running short programs in the course of answering questions. Some thirty such author languages and dialects have been developed specifically for programming conversational instruction, such as COURSEWRITER, MENTOR, PLANIT, PILOT, FOIL and CAL. Frye gives an informative general discussion of author languages.[12] Most of these languages have had limited use; at the present time little material usable in colleges and universities is available in any language other then COURSEWRITER. A few large course segments[13] have been tried with college classes.

Another approach to tutorial material is to work within a powerful existing programming language, perhaps developing subroutines which make it easier to write tutorial programs. Among the languages used in this way have been FORTRAN, PL/1, APL, SNOBOL, and SUPERBASIC.[14] These languages, or at least some of them, have the advantage of wide availability, and they do not tie the teacher down to a predetermined teaching strategy. Furthermore, they have powerful computational capabilities.

The tutorial mode which resembles programmed instruction and lends itself to reviews, drills, and self-instruction has been much admired by educational researchers, especially because of its potential for returning vast quantities of data for evaluation of performance. However, it is still very costly, variously estimated at $2.00 to

to $80.00 per student hour, depending on the assumptions made. (Bitzer at the University of Illinois has suggested a 4000-console network completely time-shared with eventual costs estimated at 25¢/student hour and $1500/terminal.[6]

The prospective user should be warned of the large gap between optimistic discussions of tutorial CAI and actually-existing materials. Except in limited areas, such as drill-work in elementary reading and arithmetic, little is currently available for classroom use. The attempt to write tutorial material quickly shows that it is extremely difficult to write good teaching material in this form, material which shows significant advantages over "conventional" programmed instruction books.[15] Grayson[16] estimates that anywhere from 10 to 200 hours of programmer's time may be necessary to produce tutorial material sufficient for one hour of terminal time, the lesser estimates being for drill and review programs.

Thus, the goal of individualized teaching, mentioned above, has certainly not been reached, and may not be practically possible. Another difficulty with existing materials is that there is no agreement on programming language; for example, the very interesting physics material written at the Massachusetts Institute of Technology using ELIZA, is not usable at other schools. So, for most teachers, the use of computer-based tutorial material is still in the future.

Simulator

Two general types of simulations might be described as black box and Monte Carlo. In the first the computer is a black box; what goes on inside need not be known by the user of the program. The student inputs information and receives the output which the computer derives by mathematical simulation of the physical situation. The student may for example, in studying the damped harmonic oscillator, input initial conditions and values of parameters such as damping constant; the machine integrates the Newtonian equation of motion and outputs a position - time table for the oscillator. Or the program can allow him to pick his own forces and initial conditions, letting him study the motion of physical systems not realizable in an ordinary laboratory.

Another application of the black box simulation is to simulate the operation and output of research tools which are much too expensive or complicated to use in the typical college laboratory. One such is a simulated high energy accelerator in the GeV region, another is a simulated mass spectrometer.[18] Such applications of the computer should become increasingly more popular as programs become available.

In the Monte Carlo method, the physical problem is replaced by an analogous but more readily soluble problem and the solutions to the latter are produced and studied. In this process the concept of randomness and the generation of random numbers play a very large part. (Many computer languages enable one to call a random numbers

generator by name as you would a sine or cosine.) So, for example, the process of radioactive decay can be considered as a process of throwing dice of many sides. Each time a certain face turns up it is removed and the dice thrown again. The decay of the number of dice thrown simulates the exponential decay of a radioactive substance.[18] Another example, one which lends itself to graphic portrayal on a computer animated film, is the diffusion of two gases as represented by a random-walk process, the size of the step varying with the temperature and mass of the gas. Computer animation is essentially a simulation process in which the graphic output, with the extremely valuable addition of motion, speaks very directly to the physical intuition of the student.

Output from a simulation can be beautifully presented on the CRT, and perhaps even more nicely on the Culler-Fried or BRAIN system, due to the slow write-rate. If numbers alone are not satisfying and graphic terminals are not available one can arrange to have results graphed on the teletype or line printer as a series of asterisks, with the abscissa (time, or the x-axis) vertically downward. Inexpensive plotters are also becoming available.[19] The important point is that the student can fiddle with the parameters and immediately see the results. In this case graphic displays are desirable.

One application of graphics to simulate experiments has been developed at IBM's Thomas J. Watson Research Center.[20] A passive network of sources, resistors, switches and meters is displayed on a CRT. By touching appropriate points of the network with the lightpen the

student can close or open switches and connect a multimeter across different terminals in order to read voltage or current. Another technique in graphic simulation is that of a "menu." For example, in network synthesis, a list or "menu" of circuit elements may be pictured on the right side of the CRT. These elements are then selected and positioned by means of a lightpen until a complete network is formed. A function can, in principle, be but into this network in order to observe what comes out at the other end, the transfer function being calculated entirely within the machine.

Gracer[21] has described a system which carries the menu technique a step further, in that the menu consists of functional blocks such as integrators, summers, dividers, relays, etc., in which the various blocks represent operations on data. Thus an analogue computer is simulated. When strung together the composite operation can be executed directly from the flow chart which appears on screen, and the result output in some appropriate form.

A student could be asked to "build" his own electrical or mechanical system on the CRT, vary its parameters and observe its properties insofar as they can be computed by the master program which interprets the display. Thus he could engage in a simulated laboratory, and "carry out" experiments to do such things as measure the charge-to-mass ratio of the electron.

One can "simulate" things which do not, in the usual sense, exist, such as electric or magnetic field lines, streamlines and "streak"

lines. To carry this still further, while the simulation of a mechanics laboratory might allow the student to work in a universe where Newton's Laws of Motion hold, it might also allow him to specify non-Newtonian laws. Or the simulation can present the student with possibilities of experience which are not available normally, even though the laws are those of the "real" world. In relativity it is often useful to assume a spacetime point of view, as if the world were spread out in front of you both spatially and temporally. An MIT Education Research Center project simulated this situation, giving the student a spacetime world on the face of a CRT. He can interact dynamically with the spacetime diagram, putting on events and worldlines, and calling on Lorentz transforms.

Simulation can be particularly useful where the system of relations connecting input and output, as in those of a multi-stage amplifier, are very complex and may consist of a medley of analytic relations, differential equations, implicit definition, and tabulated quantities which cannot be explicitly solved for the desired relationship, but must be recomputed each time.

We have not discussed "gaming", where the computer simulates the conditions under which people are required to make decisions on the basis of general knowledge and intuition. The consequences of their choices are then worked out by the program. This technique is perhaps more appropriate to the social sciences rather than the natural sciences. We are also not discussing here the development of general strategies for simulated laboratories, although such a discussion will be of greater importance as more and more is done in this direction.[22]

Calculator

It is as a calculator that we feel the computer should have its greatest immediate impact in science teaching. Rather than have students use canned subroutines they do not understand, like black boxes, it is often preferable to integrate the computer into science at an early stage (perhaps high school) by introducing notions of numerical analysis, alogrithm construction, symbol manipulation, and programming into the elementary science courses, including those for non-scientists. The simple idea is to use the computer as a computer, employing the standard computer languages. Either batch or terminal systems can be used in this way; although some computer facilities are more convenient than others, almost any existing computer on campus can be used in the way described in this section. This use of computers in science teaching is, perhaps, the oldest, and therefore the one with the most experience.[23]

An important aspect of the use of computers in teaching science, particularly where the computer is used as discussed here, is the motivational value. Many students (but not all) are excited by the computer. The young person in the United States today is well aware that he is growing up in a society increasingly influenced by computers, and this often makes him eager to use them. So a course using computers has an added element of excitement, a strong motivational factor for many students.

In introducing the computer as a tool in science courses we recognize the importance of the device in the future career of the student, and

we attempt to build on this importance. We are fast reaching the point where everyone should expect to learn something about the use of computers as a normal part of their education.

When the computer is used as a calculator in teaching science courses, the uses can be relatively trivial, or they can affect the entire structure of the course. Existing courses often lend themselves to small uses of this kind. Thus in a physics or chemistry laboratory some of the routine aspects of data analysis can be handled by the computer, relieving the student of rote work and possibly allowing more data to be used. Or existing problems can be made somewhat more realistic than the usual textbook problems of today. However, we feel that the real impact of computers on science teaching will come when teachers rethink entire courses or segments of courses, taking into account the existence of the computer just as other teaching apparatus is taken into account. Traditionally science courses have been oriented toward analytic methods, involving first algebra and trigonometry, then calculus, and then differential equations. It often comes as a surprise to the advanced student that not all problems can be solved this way. The computer allows the by-passing of the essentially algebraic approaches common in introductory courses, so new approaches to traditional courses can be attempted if the computer is part of the teaching equipment.

In the computational mode almost any existing computer language oriented toward computation can be used. With either batch or time-sharing the choice of languages may be very much restricted by what is available

from a particular computer center, so the user will not generally have a full range of choices. The commonly available batch languages for computation are FORTRAN and PL/1, and the commonly used time-sharing languages are JOSS (available with many different names), BASIC, APL, FORTRAN, and PL/1. Although there are some differences in ease of learning these languages, we believe that these differences are often exaggerated; a practical working knowledge of a useful subset of any of these languages can be acquired by a student in only a few hours, particularly if the language is learned in the context of scientific applications. Teachers who do have a choice of languages should look carefully at the newer languages such as PL/1 or APL; they avoid some problems of early languages, and offer increased power to the student programmer.

A current major problem, as in all uses of the computer in education, is the relative lack of textual materials and programs which use the computer.[24] Although some materials are published, these are often only segments of courses, or early exploration attempts. The vast majority of existing texts are pre-computer in orientation, and so do not lend themselves to the teaching techniques being suggested here. This generation of educators has not grown up with computers, so the development of such materials is essential for widespread use. Further experience may be required before the use of the computer is as clear and natural for all individuals as the use of derivatives and differential equations, with all their wealth of almost ritual detail. In certain areas, such as classical mechanics in introductory physics courses, there is already much experience, but many other areas are almost devoid of work at present.

An increasing number of scientists are finding that they can make use of computers both in teaching and in research. To stimulate innovation in this area the Commission on College Physics has sponsored workshops, and published monographs. The first such workshop was held at the University of California, Irvine, in November of 1965; participants from both physics and computer science joined in producing a report, The Computer in Physics Instruction. The report of the conference, and also of a later conference on new instructional materials, held at the University of Washington in the summer of 1966, is available from the Commission on College Physics.[25]

Following the Irvine conference the Commission on College Physics has also sponsored continuing development of computer related physics teaching materials, mostly in the computational mode. A recent publication is Introduction Computer-Based Mechanics, A One Week Sample Course.[26] This publication is a self-contained slice of curriculum covering the elementary mechanics of the harmonic oscillator, intended for use in all beginning physics courses. One week of time in a typical beginning course is assumed. It consists of a Student Manual and an extensive Teacher's Guide for three lectures and one laboratory session. To make the monograph usable in as wide a variety of circumstances as possible, flow charts are used extensively and four versions are obtainable, each using one of four languages, FORTRAN, BASIC, JOSS, and PL/1. This type of partially language-free presentation may become common in textbooks in the future. The Teacher's Guide tries to ease the path for the teacher with no previous computer experience; it offers practical advice on using existing computer facilities at the teacher's school.

The Commission on College Physics has also established a Computer Library for Instruction in Physics (CLIP) to collect and distribute programs useful for physics education. Program listings and ancillary materials are available from the Commission after their abstracts have been refereed and accepted for publication in the Americal Journal of Physics.[27] Several such articles have appeared.[28]

With graphic output, which we suggest has a great future scientifically and educationally, the results of computations can be displayed graphically very rapidly on the CRT. With interactive CRT terminals, the user can do interesting computations and see the results immediately without the intermediate step of plotting them. He can also manipulate his view of the xy-plane, magnifying, telescoping, changing scale or translating as desired by means of lightpen or keyboards.

Educational Philosophy

We stress again that no review of this type can claim to be complete. The reader should consult other surveys of the field for balance.[20,29]

In discussing the introduction of the computer into the science curriculum we need to be concerned not only with how the computer can be a useful tool, but how it will alter the style and content of science education. Knowledge of the unique conceptual advantages and problems of the computer should be acquired early in the curriculum if the computer is to become a fundamental part of the scientist's problem-solving repertory. Ultimately, we may see the methods of numerical analysis and the calculus

of finite differences, and other symbol manipulating techniques fully integrated into the science curriculum in anticipation of their relevance to the utilization of the computer. These techniques will not supplant the standard mathematical analysis which has traditionally accompanied the scientific curricula, but rather complement the mathematics by enabling the student to explore a broader range of more meaningful problems. Undoubtedly, fundamental science will still be heavily dependent on analytical procedures, and even applied science will best be done by a combination of analytic and numerical methods. Both approaches will be needed, and increasingly more problems may be resolvable only by a combination of them. Computers can certainly be mis-used; we must give students insight into the reasonable use of computers.

The potential scientist should learn, in the context of his chosen discipline, to use the standard programming languages. This early introduction of an important tool is almost essential today; to educate a scientist of any type without detailed knowledge of computer capabilities and limitations is unfortunate. We believe that the student will best learn to employ computers if he sees them in the areas where they are useful, and if he sees numerical and analytic methods as complementary ways to solve mathematical problems, each with strengths and weaknesses.

The nonscience major will increasingly encounter computers also in the contemporary world, so this early introduction makes sense for him also, as part of his liberal education. We agree with the report of the President's Scientific Advisory Committee,[23] which recommends that "Colleges and Universities....take steps to provide all students needing

such facilities with computing services at least comparable in quality to that now available at the more pioneering schools.[30]

More important for our purposes here, with emphasis on teaching, the computer as a computer is often a valuable pedagogical device. Many areas of science, particularly in physics, are heavily dependent on the mathematical level and maturity of the student. Often the teacher cannot proceed in a direction he would desire, because the mathematical capabilities of his students are insufficient to make this direction viable. The numerical approaches may allow alternate mathematical paths through the material; thus the study of classical mechanics at the beginning level can use the laws of motion as differential equations.

With the computer, both student and teacher are no longer restricted to the classical setpiece problems by the students' lack of mathematical sophistication, but are at least partially liberated from traditional mathematical limitations.

Courses can take a new and more meaningful form. Furthermore, by providing a fast and efficient way to do difficult and time-consuming calculations, we can guard against losing sight of the basic principles amid a welter of mathematical or calculational detail. For the future scientists, as well as for students in other areas, direct contact with computers in the context of his scientific studies should begin at the earliest possible moment in his education. If computers are to be used widely, students must grow up with a sophisticated attitude toward them. One must stress that a numerical method is as respectable in approach

to problems as in an analytical method or looking a function up in a table. A procedure, an algorithm, is a solution to a physical problem; it simply uses different techniques, a different approach. From the research point of view, no scientist can afford to neglect any available technique. From the pedagogical standpoint one cannot ignore the fact that students find computers exciting, particularly when they are actively involved in constructing and running their own programs. In a day of declining space enrollments this is a strong incentive to use the computer in the classroom.

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